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COLLINS SIGNAL

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# Multiband Antenna for High Frequencies

## Section I. Practical Data:

A HIGH FREQUENCY antenna and associated transmission line, capable of efficient operation over a wide range of frequencies, has been urgently needed. Amateurs are rarely fortunate enough to have sufficient space for erecting more than one antenna, and commercial high-frequency stations are also frequently located in restricted quarters where separate antennas for each channel cannot be used.

The ordinary high-frequency antenna consists of a doublet operated at its fundamental (the length equal to one-half wave length) or at a harmonic. Such antennas are popularly classified by the type of feeder system employed, such as "Center Fed," "End Fed or Zeppelin," "Single-wire Hertz," "Matched Impedance with Y connected feeders," etc. Only by connecting the feeders into the center of the doublet can the antenna and feeder system be kept electrically symmetrical as the frequency is varied. Unfortunately, the impedance at the center of the antenna changes with the frequency, and any ordinary arrangement for matching the transmission impedance to the antenna impedance can be effective at only one frequency. Furthermore, the effective electrical height (which may be different from the physical height above ground) has a marked effect upon the antenna resistance, and an impedance matching system which is effective at only one value of antenna impedance cannot be counted on to give correct energy transfer to the antenna unless it is adjusted for each particular installation.

The problem, then, resolves itself into the designing of a transmission line which operates efficiently over a wide range of terminating or antenna impedances. The usual two-wire line, constructed of two No. 12 wires spaced about six inches and having a characteristic impedance of about 600 ohms, is not satisfactory for this purpose. For example, such a line one-quarter wave length long connected to the center of a one-half wave length doublet will not be terminated in its characteristic impedance of 600 ohms, but in the antenna resistance of about 75 ohms, and due to the properties of such a line the input impedance at the transmitter end will be about 5,000 ohms (mathematical study will be reserved for the second section of this article and is not essential for a practical understanding of the system). An input impedance as high as 5,000 ohms is undesirable because it is difficult to transfer power to it, because a slight capacity unbalance will cause serious radiation from the line, and because line losses are high due to poor power factor, i. e., pronounced standing waves.

In practice the impedance at the center of a horizontal antenna varies between about 75 ohms and 1200 ohms as the frequency is varied. The lower values occur when the antenna length is one-half wave length, three one-half wave lengths, five one-half wave lengths, etc., and the impedance is highest for frequencies making the antenna length one or more full wave lengths long. If a transmission line with a characteristic impedance of 300 ohms (the geometric mean between 75 and 1200) is used, the standing waves will be a minimum at all frequencies, and the input impedance will remain at all times a manageable value not exceeding 1200 ohms. A 300 ohm line can be constructed of two ¼ inch tubes spaced 1½ inches by means of ceramic blocks at intervals of about 20 inches. The blocks can be located by crimping the tube slightly on either side of the block. A 50 foot copper line of this type weighs 10.9 pounds and is not difficult to support from the center of the antenna. If necessary, aluminum instead of copper tubing may be used to reduce the load on the antenna supports when the vertical part of the transmission line is greater than 50 feet. A line so constructed has surprisingly low loss. Figures 1 and 4 show the actual data, but the following excerpts indicate the minimum efficiency obtained for a line 100 feet long terminated in either 70 or 1200 ohms.

| Frequency | Efficiency |
|---|---|
| 3000 kc. | 98.5% |
| 7000 kc. | 98 % |
| 14000 kc. | 97 % |

By way of comparison it is interesting to note that a 100 foot twisted pair transmission line of popular make has the following efficiency when terminated in its characteristic impedance:

| Frequency | Efficiency |
|---|---|
| 3000 kc. | 95% |
| 7000 kc. | 84% |
| 14000 kc. | 68% |

Of course, an antenna with twisted pair feeders can only be used on one band.

A 600 ohm two-wire line 100 feet long terminated in 70 ohms has the following efficiency when **properly balanced:**

| Frequency | Efficiency |
|---|---|
| 3000 kc. | 94% |
| 7000 kc. | 92% |
| 14000 kc. | 89% |

In practice, slight unbalances in a 600 ohm line materially reduce the efficiency, whereas the 300 ohm line is not so susceptible to loss in efficiency.

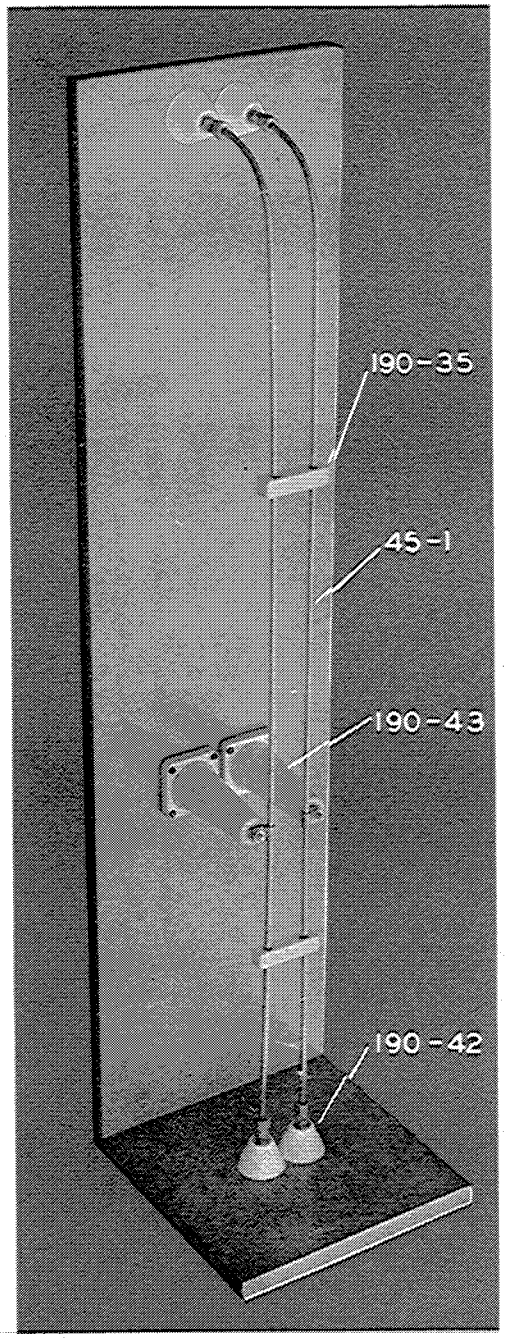
In view of the above information it is seen that an antenna can be made to work very efficiently over a wide frequency range and with any antenna im-

## • Multiband Antenna for High Frequencies (Continued)

pedance between 75 and 1200 ohms by the simple expedient of using a specially constructed transmission line. Several different models of such an antenna system are possible and Table I shows representative combinations designed for use on amateur bands. In each of the arrangements shown in Table I the length of the multiband transmission line is so chosen that the reactance at the transmitter end is negligible and the line can be coupled to the output tank circuit of the transmitter by a simple pickup coil. An impedance matching network need not be used provided the number of turns in the pickup coil is continuously adjustable.

In cases when it is not convenient to use a transmission line as long as is shown in Table I it is, of course, entirely practicable to reduce the length of the line to a convenient value and build out the equivalent electrical length by inserting an impedance matching network between the transmitter and the line. When such a network is used the line can be made any length, and then the only important dimension is the antenna itself. The only precaution which must be observed is that the transmission line should not be ⅛, ⅜, ⅝, etc. wave length long at any of the operating frequencies. If the line happens to be cut to a length equivalent to an odd number of ⅛ wave lengths, trouble may be encountered due to the network transmitting not only the fundamental frequency but also harmonic frequencies. This difficulty can be overcome by proper adjustment of the impedance matching network, but a discussion of this subject will be reserved for a later article. In general it is better to avoid these specific lengths.

Table I can be used directly for designing multiband antennas for amateur use. It will be noticed that the antenna lengths shown are an even number of one-quarter wave lengths long at the lowest and highest frequencies. In the case of antennas for 14,000 kc. and 4,000 kc. operation the frequencies are not harmonically related, but the lengths are chosen for the highest frequency, and they are also approximately right for the lower frequency where small variations in length do not represent very large percentages of a wave length.

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The constructional model illustrated above was built to show the manner of assembly. Items and their type numbers are as follows: Spacers (190-35); Stand-off Insulators (190-43); Feed-through Insulators (190-42); Seamless Copper Tubing (45-1).

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In designing similar systems for other groups of frequencies, the antenna length should be (k-.05) 492,000/f feet where f is the frequency in kilocycles and k is the number of half-wave lengths. Thus, for two or more frequencies integral values of k should be chosen to give approximately the same length and the exact length should be that for the highest frequency.

For example, consider model A antenna. At 14,300 kc. and k=4 or a two wave length antenna the length is 136 feet. This length is also correct for f=7,050 and k=2 or f=3440 and k=1. The frequency range of the amateur bands may be tolerated by this length even though the transmission line be terminated in an antenna impedance not a pure resistance.

The feeder length should be determined by the relation 234,000 m/f feet where f is the frequency in kilocycles and m is the number of quarter-wave lengths. That is, the 66 ft. feeder of model A antenna is one wave length at 14,200 kc., a half-wave length at 7,100 kc., and one-quarter wave length at 3,550 kc.

A slight variation from the above procedure is indicated in Model G. In this antenna the length of 103 feet is 1½ wave lengths at 14,100 kc. and approximately ¾ and ⅜ wave lengths on the 40 and 80 meter bands. The feeder length of 82.5 feet is 1¼ wave lengths at 14,200 kc. and approximately ⅝ and 5/16 wave lengths at the 40 and 80 meter bands. That is, on 40 and 80 meters the transmission line is terminated in an impedance largely reactive but is of such length that the impedance at the input to the transmission line is approximately a pure resistance. The loss in the transmission line is slightly larger under this condition, but this antenna may be used successfully where space is a factor.

Many amateurs are using so-called Zeppelin antennas rather than antennas fed at the center because their transmitters happen to be located nearer the end than the center of the antenna and the transmission line is shorter if it is connected to the end of the doublet. The Zeppelin antenna is an inherently unbalanced system (Zeppelin feeders balanced for equal currents are not balanced for equal phase and vice-versa) and a considerable portion of the energy is una-

## • Multiband Antenna for High Frequencies (Continued)

voidably radiated from the feeders, which radiation may or may not be useful for transmission. The multiband system just described should receive preference over the Zeppelin arrangement even if the transmitter is close to one end of the antenna, because the additional loss introduced by running the transmission line horizontally to a point under the center of the antenna, then vertically to the antenna itself will be entirely negligible, and probably will be considerably less than the loss in Zeppelin feeders. The multiband antenna is readily supported from suitable stand-off insulators and can be carried around corners by making bends having a minimum radius of about 10 inches. It is entirely feasible to double back the line in trombone fashion, if desired, to obtain a length which will obviate the use of an impedance matching network.

The directional properties of the multiband antenna vary as the frequency is changed. The directivity is not ordinarily considered in amateur installations where transmission is carried on in random directions. There are a large number of possible combinations giving different degrees of directivity and a review of this subject with special reference to multiband operation will be attempted in a second article.

TABLE I

| MODEL | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| Antenna Length—Feet | 136 | 136 | 275.5 | 250 | 67 | 67 | 103 |
| Feeder Length—Feet | 66 | 115 | 99 | 122 | 65 | 98 | 82.5 |
| Frequency Range M.C. | 3.7– 4.0<br>7.0– 7.3<br>14.0–14.4 | 3.7– 4.0<br>14.0–14.4 | 1.7– 2.0<br>3.7– 4.0<br>7.0– 7.3<br>14.0–14.4 | 1.7–2.0<br>3.7–4.0 | 7.0– 7.3<br>14.0–14.4<br>28.0–29.0 | 7.0– 7.3<br>14.0–14.4<br>28.0–29.0 | 3.7– 4.0<br>7.0– 7.3<br>14.0–14.4 |
| Nominal Input Impedance | 1200Ω<br>All<br>Bands | 75Ω<br>All<br>Bands | 1200Ω<br>160–80–20 m,<br>75Ω<br>40 m | 1200Ω<br>All<br>Bands | 75Ω 40 m<br>1200Ω 20 m<br>10 m | 1200Ω<br>All<br>Bands | 1200Ω<br>All<br>Bands |

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## Section II

## • Transmission Line Loss Calculation and Measurement

It has been the purpose of this project to study the various types of radio frequency transmission lines that might be used as connecting links between a radio transmitter and the radiating system proper. In this connection it is desirable to study the losses occurring in the line when terminated in its characteristic impedance —and in some cases when terminated in a different value. This latter is the condition of operation of a section of line used as a transformer matching section between two impedances, or as a resonant feeder. It is also necessary to check the calculated characteristic impedance by experimental means and to determine experimentally the velocity of propagation of the electromagnetic waves along the line. The velocity of propagation is necessary to determine accurately the phase shift in sections of line used in directional radiation systems.

There are essentially three types of lines which are used extensively in the transmission of radio frequency power. They are, namely, two wire balanced line, coaxial transmission line and twisted pair. The two wire line may be essentially of two types. It may be constructed of solid wire with nominal spacing and having a characteristic impedance some place in the region of 600 ohms. This type of line is normally used as a properly terminated transmission line. The two wire line may, however, be made of copper or aluminum tubing of ¼ or ½ inch diameter and relatively close spacing. The characteristic impedance of this type of line may be in the region of 150 to 300 ohms. This type of line is very suitable for use as matching sections in which it is desired to get high efficiency in the presence of standing waves. The coaxial or concentric transmission line has a characteristic impedance in the region of 70 to 125 ohms and is inherently an unbalanced transmission line of quite low loss. It is usually used to transmit power from the transmitter to an unbalanced load—such as feeding an antenna against ground. It is very popular with broadcasters due to its high efficiency and to the fact that it may be run on or under the ground without further insulation or increased loss, thus giving neat appearance as well as a factor of safety where high power is involved. A concentric line may also be used to transmit power to a half-wave doublet antenna. It is well adapted for this purpose since the impedance of a half-wave doublet in free

## • Transmission Line Loss Calculation and Measurement (Continued)

space is 73 ohms, giving a good match with the concentric line. Twisted pair is sometimes used to feed a half-wave doublet. The characteristic impedance of twisted pair may be made in the order of 70 ohms by proper selection of the dielectric. The twisted pair is less expensive than some other types of lines but also has somewhat higher losses.

Considering, first, the two wire line when terminated in its characteristic impedance: at high frequencies the resistance of a circular conductor is:

$$R = \sqrt{\frac{\rho f}{a}} \times 10^{-9} \text{ ohms/cm}^*$$

Where $\rho$ is the resistivity in electromagnetic units.

$f$ is the frequency in cycles per second.

and $a$ is the conductor radius in cm.

This resistance formula neglects the reaction on skin effect of the proximity of the conductors. The following correction may be applied:

$$c = \frac{b}{\sqrt{b^2 - 4a^2}} \quad \dagger$$

Where a is radius of conductors

and $b$ is separation center to center.

This correction may be neglected except for the lines constructed of tubing having close spacing.

From transmission line theory the characteristic impedance and the propagation constant are given by:

$$Z_0 = \sqrt{\frac{Z}{Y}}$$

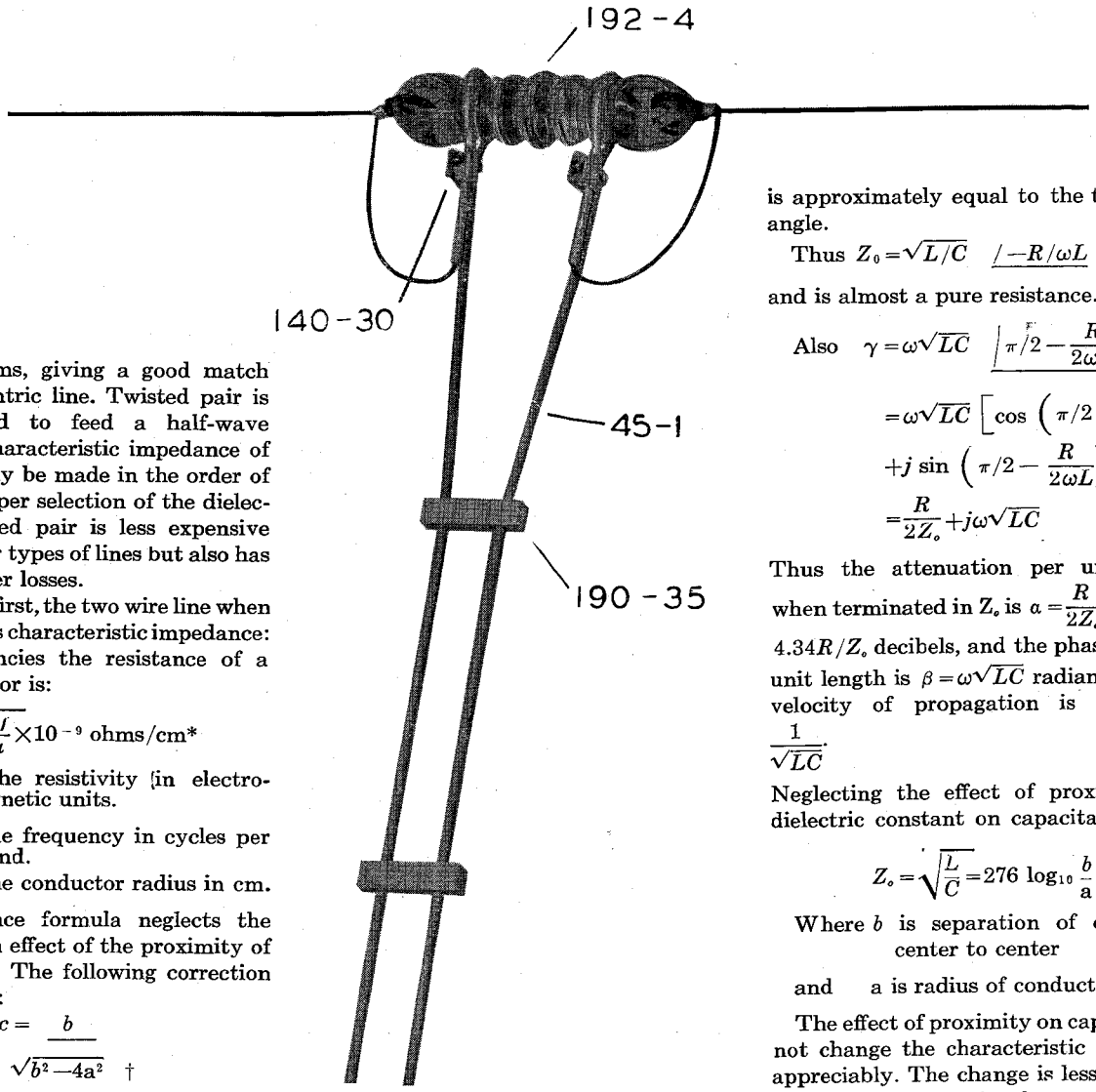
and $$\gamma = \sqrt{ZY}$$

Where $Z$ is the impedance per unit length.

and $Y$ is the admittance per unit length.

*(A. Russell Phil. Mag. April, 1909.)

† (S. P. Mead Bell System Technical Journal, pg. 327, 1925.)

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FITTINGS FOR THE CENTER OF THE MULTIBAND ANTENNA

The special clamp (140-30) makes a permanent connection between the line and the antenna wire without soldering. Center insulator (192-4) is also illustrated.

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For a given line:

$$Z = R + j\omega L$$

and $$Y = j\omega C$$

neglecting leakage conductance.

Using the fact that for a low loss line $\omega L \gg R$ and the angle of $Z$ is approximately $\pi/2$ gives

$$Z = \omega L \angle \pi/2 - R/\omega L$$

since for small angles the angle in radians is approximately equal to the tan. of the angle.

Thus $Z_0 = \sqrt{L/C} \quad \angle -R/\omega L$

and is almost a pure resistance.

Also $\gamma = \omega\sqrt{LC} \quad \angle \pi/2 - \frac{R}{2\omega L}$

$$= \omega\sqrt{LC}\left[\cos\left(\pi/2 - \frac{R}{2\omega L}\right) + j \sin\left(\pi/2 - \frac{R}{2\omega L}\right)\right]$$

$$= \frac{R}{2Z_0} + j\omega\sqrt{LC}$$

Thus the attenuation per unit length when terminated in $Z_0$ is $\alpha = \frac{R}{2Z_0}$ nepers or $4.34R/Z_0$ decibels, and the phase shift per unit length is $\beta = \omega\sqrt{LC}$ radians, and the velocity of propagation is $V = \omega/\beta = \frac{1}{\sqrt{LC}}$.

Neglecting the effect of proximity and dielectric constant on capacitance:

$$Z_0 = \sqrt{\frac{L}{C}} = 276 \log_{10} \frac{b}{a} \text{ ohms}$$

Where $b$ is separation of conductors center to center

and a is radius of conductor

The effect of proximity on capacity does not change the characteristic impedance appreciably. The change is less than one-half of one percent for the case of ¼-inch tubing spaced 1 inch center to center. In air the dielectric constant may be taken as unity.

As an illustrative example of the loss occurring at radio frequencies on a transmission line terminated in its characteristic impedance, the computed loss in decibels per 100 feet has been calculated for three cases:

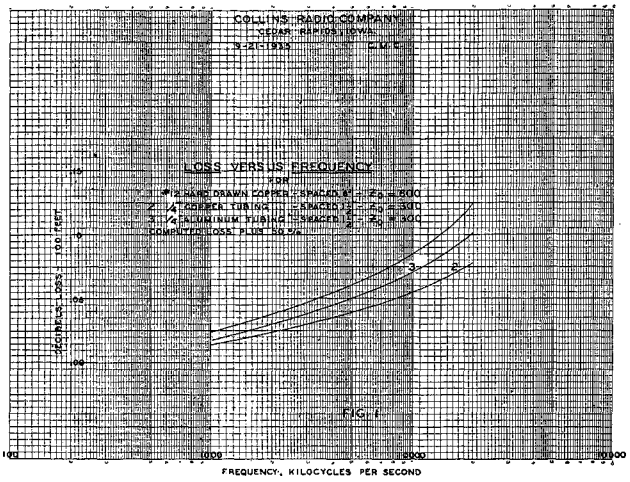
(1) No. 12 Hard-drawn wire spaced 6 inches with a characteristic impedance of 600 ohms.

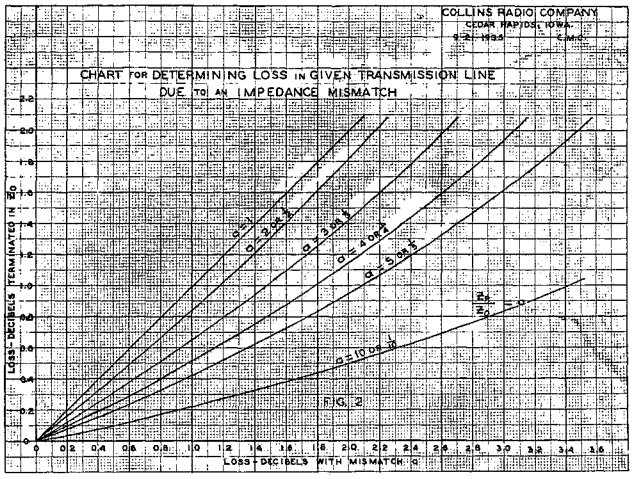
(2) ¼ inch copper tubing spaced 1½ inches with a characteristic impedance of 300 ohms.

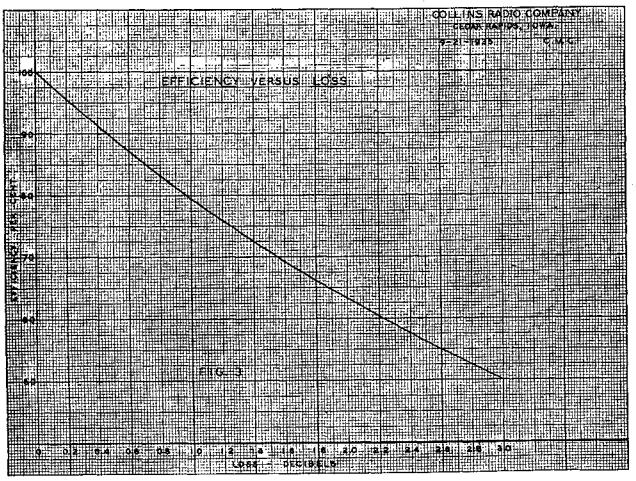
(3) ¼ inch aluminum tubing spaced 1½ inches.

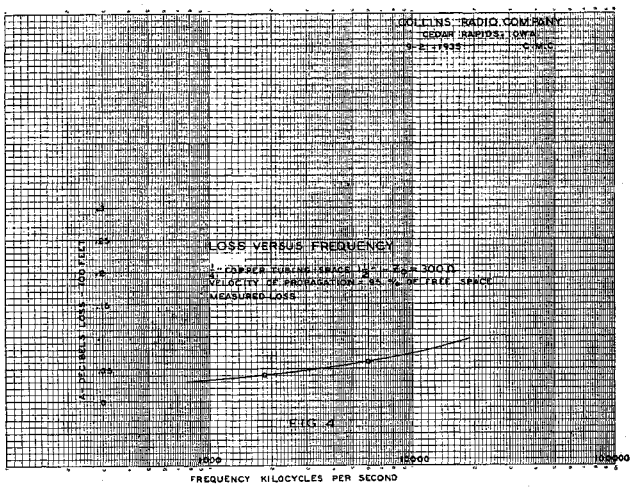
*(Continued on Page 8)*

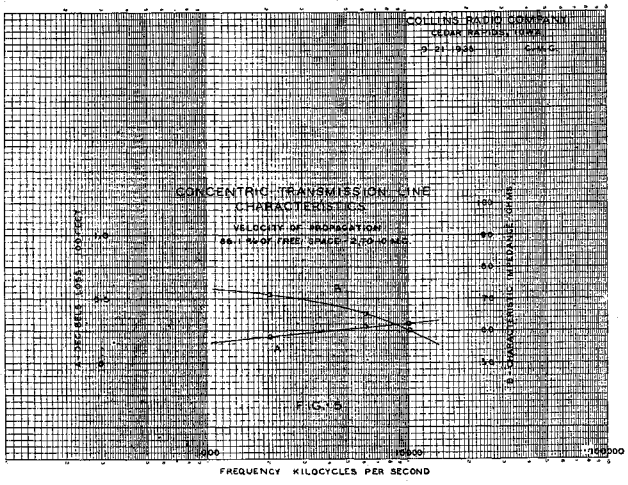
## • Transmission Line Loss Calculation and Measurement (Continued)

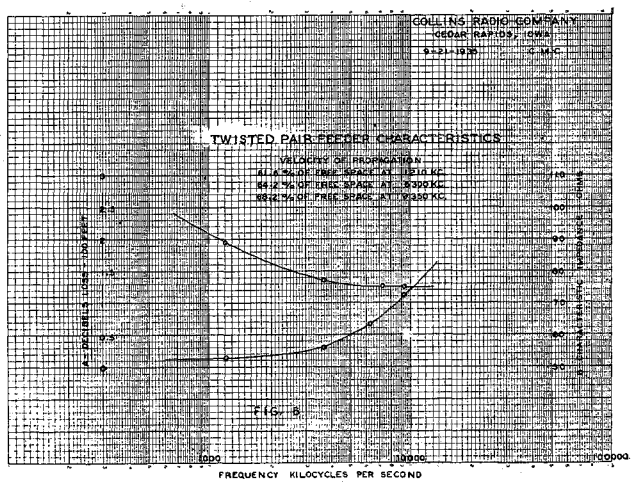




COLLINS RADIO COMPANY
CEDAR RAPIDS, IOWA
CHART FOR DETERMINING LOSS IN GIVEN TRANSMISSION LINE DUE TO AN IMPEDANCE MISMATCH
FIG. 2
LOSS-DECIBELS WITH MISMATCH



## • Transmission Line Loss Calculation and Measurement (Concluded)

It has been stated in previous articles on the subject that the measured loss at radio frequencies is 50% larger than computed values. This agrees quite well with tests made in our laboratories. The computed values increased by 50% have been plotted in Fig. 1 for the three cases mentioned. Actual tests on the ¼ inch tube line showed the velocity of propagation to be 5% less than that of free space.

If the two wire line is terminated in an impedance not equal to the characteristic impedance the loss is increased due to the presence of standing waves. The loss under these conditions can also be calculated from the well known transmission line equations in terms of hyperbolic functions.

$$I_S = I_R \cosh \gamma l + E_R/Z_o \sinh \gamma l$$

$$E_S = E_R \cosh \gamma l + I_R Z_o \sinh \gamma l$$

Where subscripts $S$ and $R$ denote sending and receiving currents and voltages respectively. Taking $Z_o$ as a pure resistance $R_o$ and terminating the line in a complex impedance $Z_R = E_R/I_R$

$$\text{Where } Z_R/Z_o = \frac{R_R}{R_o} + j\,\frac{X_R}{R_o} = a + j\,b.$$

From these equations the input power to the line may be calculated as

$$P_i = aR_oI_R^2\left[\cosh 2al + \frac{a^2+b^2+1}{2a}\sinh 2al\right]$$

The output power into $Z_R$ is

$$P_o = I_R^2R_R = aI_R^2R_o$$

The line loss in decibels is then given as $L = 10\ log_{10}P_i/P_o = 10\ log_{10}$

$$\left[\cosh 2al + \frac{a^2+b^2+1}{2a}\sinh 2al\right]$$

If the termination is a pure resistance, then $b = o$. Also if this termination is a resistance equal to $Z_o$ a $= 1$ and the loss is $8.68al$ in decibels. Thus if the loss is known when the line is terminated in $Z_o$ the above relations may be used to determine the loss when the line is terminated in a value other than $Z_o$. In Fig. 2 there have been plotted the values of the loss in decibels for various degrees of mismatch versus the loss in decibels for the same length of line when terminated in $Z_o$.

In Fig. 3 there has been plotted for convenience the efficiency versus loss in decibels as calculated from the relations

$$\text{Loss } (db) = 10\ log_{10}\frac{P_i}{P_o}$$

$$\text{Eff } (\%) = 100\,\frac{P_o}{P_i}$$

This is useful in obtaining the efficiency of any length of line with any degree of mismatch. The loss of the given length of line when terminated in $Z_o$ can be determined from Figs. 1, 4, 5 and 6 by direct ratio. For the degree of mismatch for which you desire the efficiency the loss can be found from Fig. 2 and from this loss the efficiency is read from Fig. 3. Thus, for example, 250 feet of ¼ inch copper tubing spaced 1½ inches and terminated in 60 ohms resistance has an efficiency of 90% at 14 megacycles.

Figs. 4, 5 and 6 show the results of experimental measurement of losses on three types of lines. Fig. 4 is the ¼ inch copper tubing line computed previously. Fig. 5 is a small size coaxial transmission line made up of No. 12 wire inside of ⅜ inch copper tubing and centered by Isolantite beads spaced 1¼ inches. Fig. 6 is a type of twisted pair often used for radio frequency transmission. It consists of two No. 12 wires with a spacing approximately $\frac{5}{32}$ inch. Each wire is rubber covered, and the two wires are twisted together and covered with an impregnated braid. The loss for this type of line increases more rapidly with frequency than the theoretical treatment would indicate. This is due to the addition of the dielectric loss of the insulation to the copper loss and skin effect.

The characteristic impedance of a coaxial transmission line is 138 $log_{10}$ $r_1/r_2$ ohms.

Where $r_1$ is the inner radius of the outer conductor

and $r_2$ is the outer radius of the inner conductor.

For the coaxial line measured $r_1 = .15$ inches and $r_2 = .0404$ inches, giving a theoretical value 78.7 ohms for the characteristic impedance. The measured value is slightly less. This can be explained by the fact that the inner conductor of No. 12 wire is slightly oversized, and the capacity is increased partly by the dielectric constant of the Isolantite beads. The velocity of propagation is 15% lower than for free space.

In the twisted pair transmission line the velocity is reduced by 35 to 40% from the value for free space due to the increased dielectric constant.

—L. M. Craft

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The 45A Transmitter (see October Signal) has rapidly won an important place for itself. The photograph shows a group of 45A's under construction. An effort is being made to speed up production to meet the unexpected number of sales.

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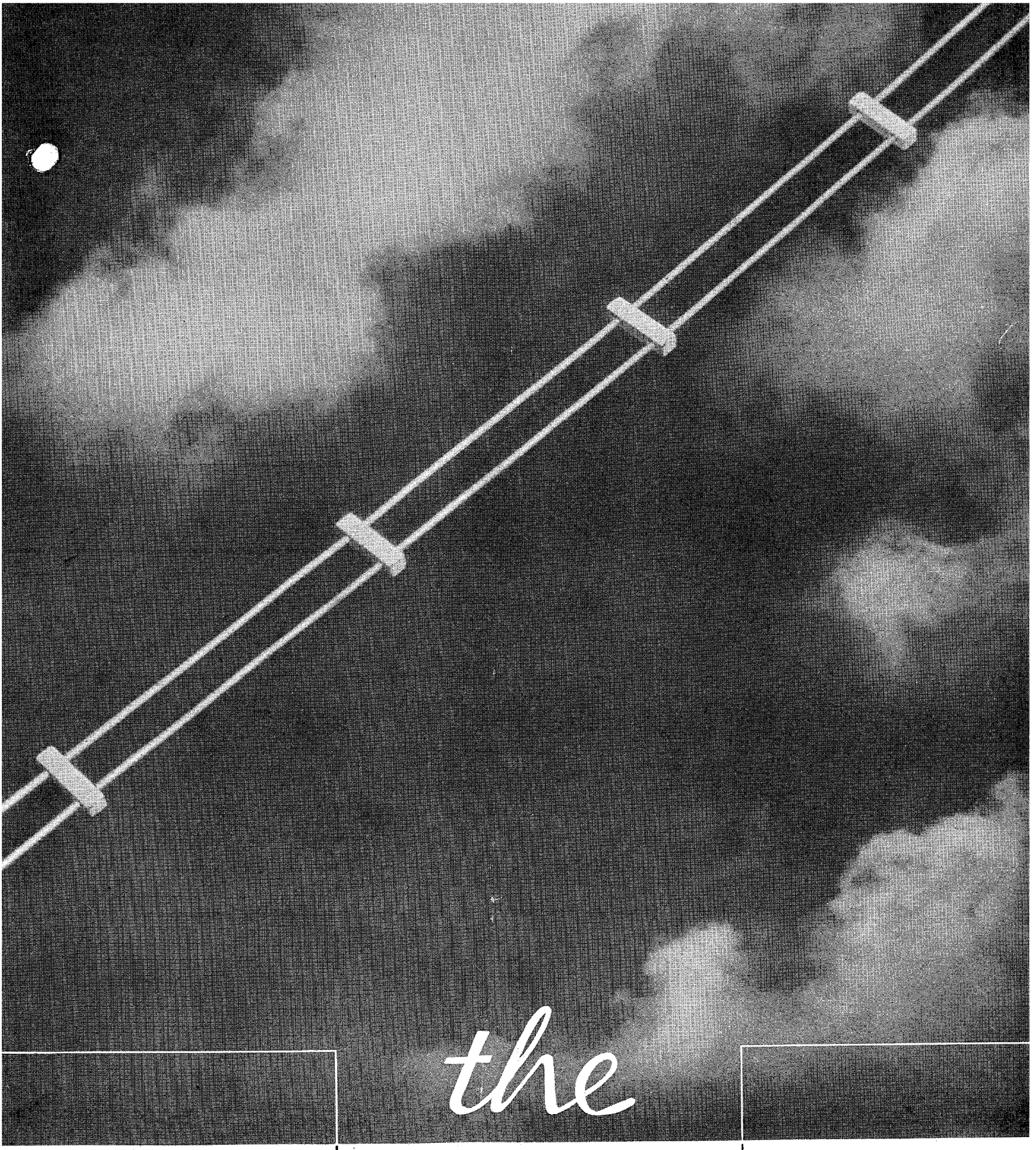

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